Novel Concepts to Expand Iron & Steelmaking Processes

Professor Brajendra Mishra
Metal Processing Institute
Worcester Polytechnic Institute

Iron & Steel Workshop at ARPA-E
Aug 31 – Sep 1, 2021

Global Steel Production: Ore Consumption

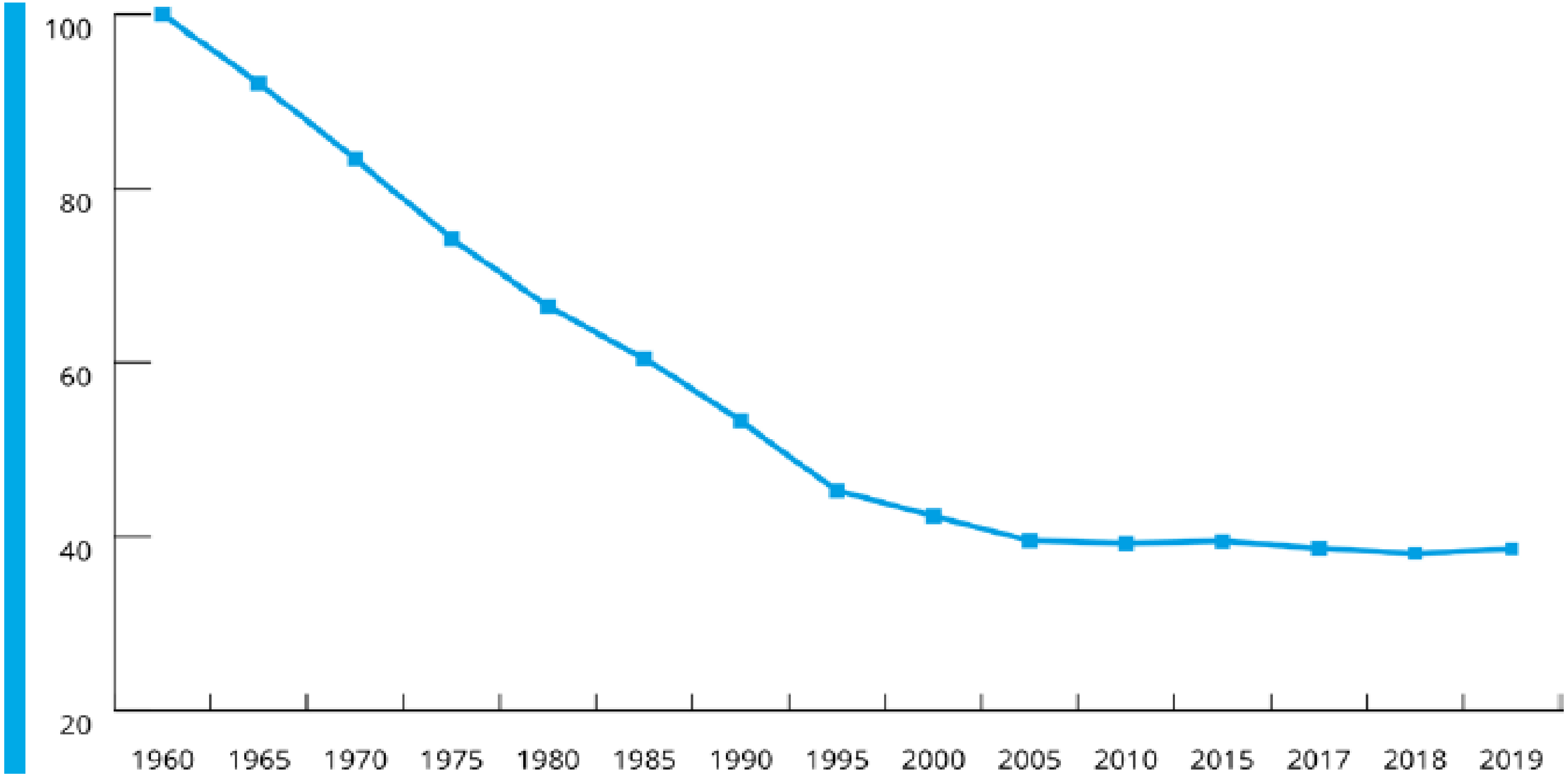
Iron ore demand to go down after 2025 – steel demand flat and shift to scrap-based steelmaking

Indicator (billions of tonnes)	2015	2020	2025	2030	2035	CAGR, %
Apparent steel use	1.50	1.73	1.81	1.85	1.87	1,1%
Crude steel production	1.62	1.86	1.95	2.00	2.02	1,1%
BOF	1.21	1.31	1.30	1.27	1.22	0,0%
EAF	0.41	0.56	0.65	0.73	0.81	3,5%
Demand for iron ore	**2.01**	**2.21**	**2.24**	**2.23**	**2.16**	**0,4%**
Balance of scrap	0.12	0.05	0.03	0.02	0.03	-6,2%
Demand for scrap	0.55	0.70	0.78	0.84	0.90	2,5%
Supply of scrap	0.68	0.76	0.81	0.87	0.94	1,6%
Home scrap	0.12	0.14	0.14	0.15	0.15	1,1%
Prompt scrap	0.22	0.23	0.24	0.25	0.27	1,0%
Obsolete scrap	0.33	0.39	0.43	0.47	0.52	2,2%

2035 (IV) - Net exports of finished steel in China is 100 Mt; BOF/EAF in China is 80/20; BOF/EAF in RoW - 50/50

Global Steel Production: Energy Efficiency

Energy efficiency of iron & steelmaking has improved by 60% in 45 years through process innovations.

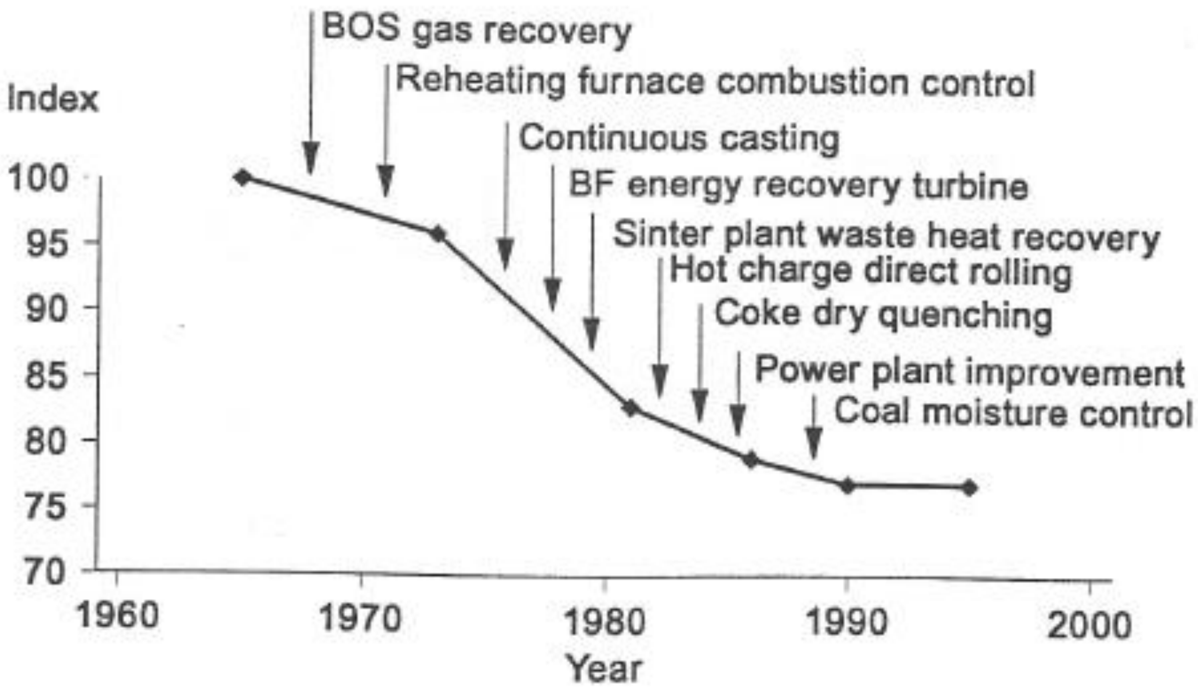


Indexed global energy consumption per tonne of crude steel production

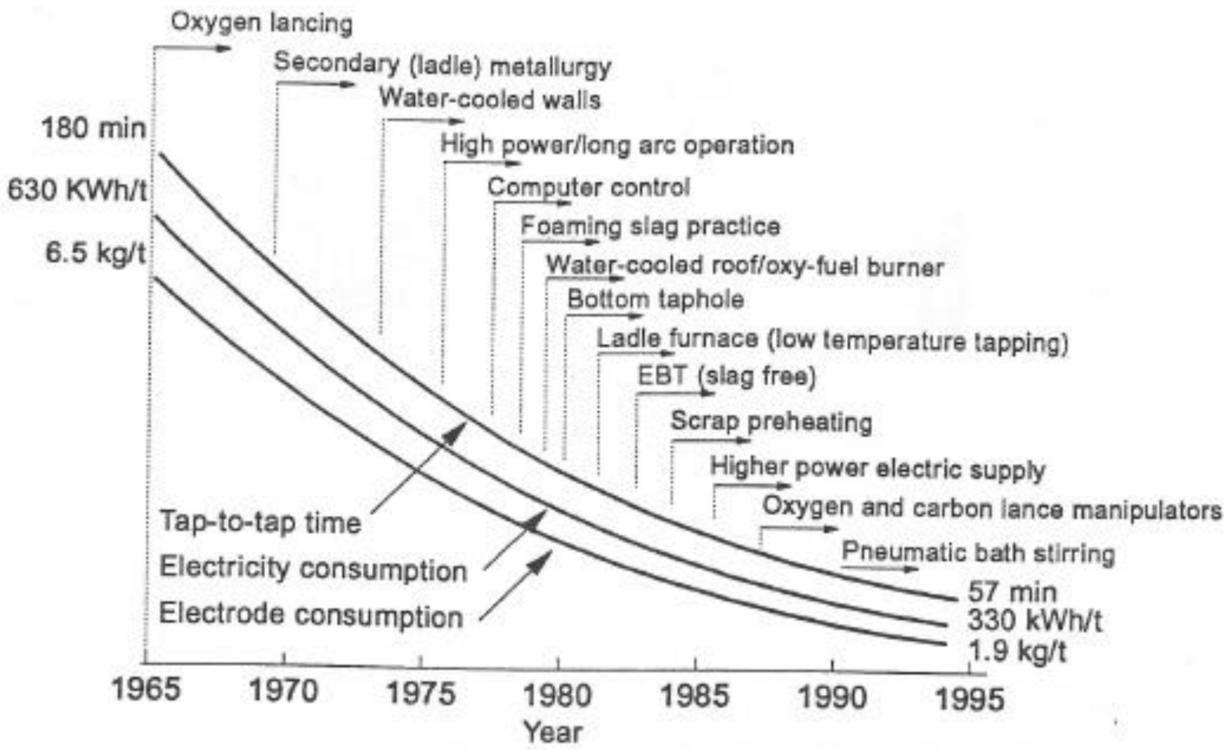
Source: World Steel Association

Global Steel Production: Energy Efficiency

Process Innovations in BF/BOS



Process Innovations in EAF



Source: World Steel Association

Alternative processing to “business as usual”

- **Non-conventional processes: successes and challenges**

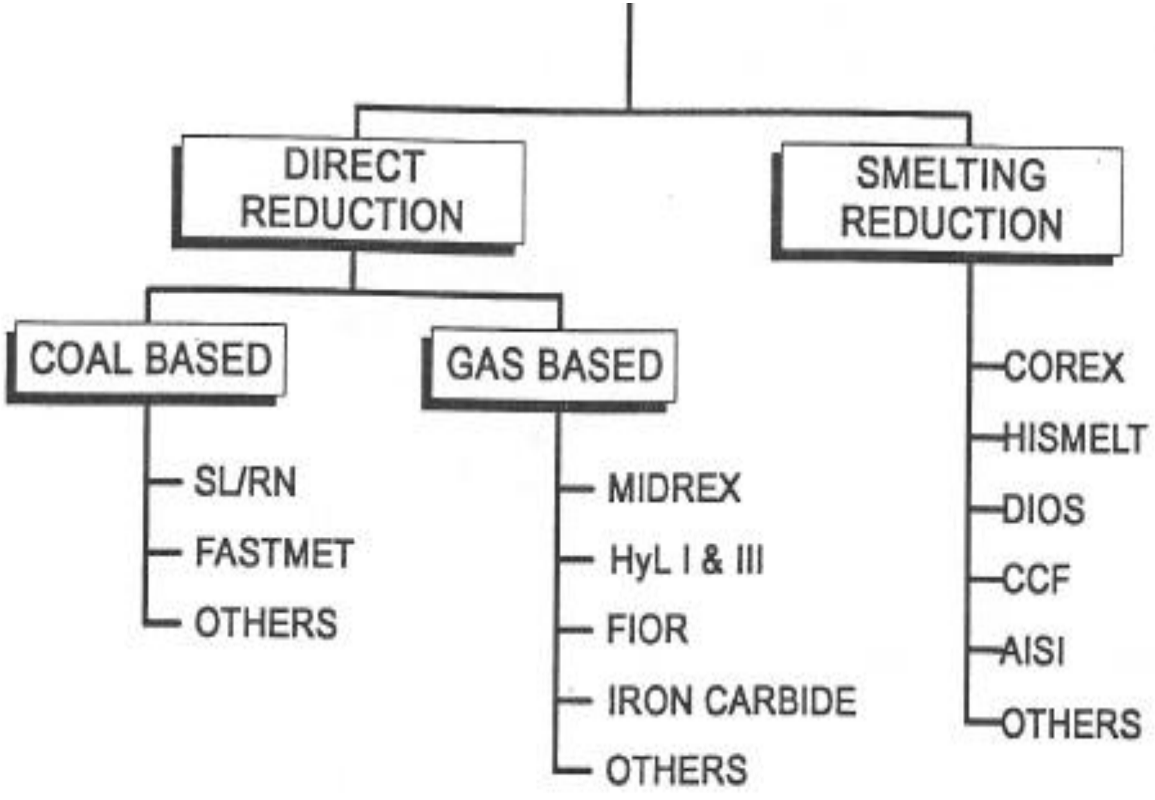


TABLE 1

Balanced Process Chemistry for Iron Carbide Formation

I. Fe_2O_3 (hematite iron ore) Feed

$$3Fe_2O_3 + 11H_2 + 2CO = 2Fe_3C + 11H_2O$$

H_2: 0.515 Standard $m^3/kg\ Fe_2O_3$
CO: 0.094 Standard $m^3/kg\ Fe_2O_3$
Fe_3C: 0.7495 $kg/kg\ Fe_2O_3$

II. Fe_3O_4 (magnetite iron ore) Feed

$$Fe_3O_4 + 5H_2 + CO = Fe_3C + 5H_2O$$

H_2: 0.484 Standard $m^3/kg\ Fe_3O_4$
CO: 0.097 Standard $m^3/kg\ Fe_3O_4$
Fe_3C: 0.7754 $kg/kg\ Fe_3O_4$

Approximately 1.35 tonnes of hematite and 12 gigajoules of natural gas are required the production of one tonne of iron carbide.

Source: Iron Carbide Holding

Non-ore based iron sources

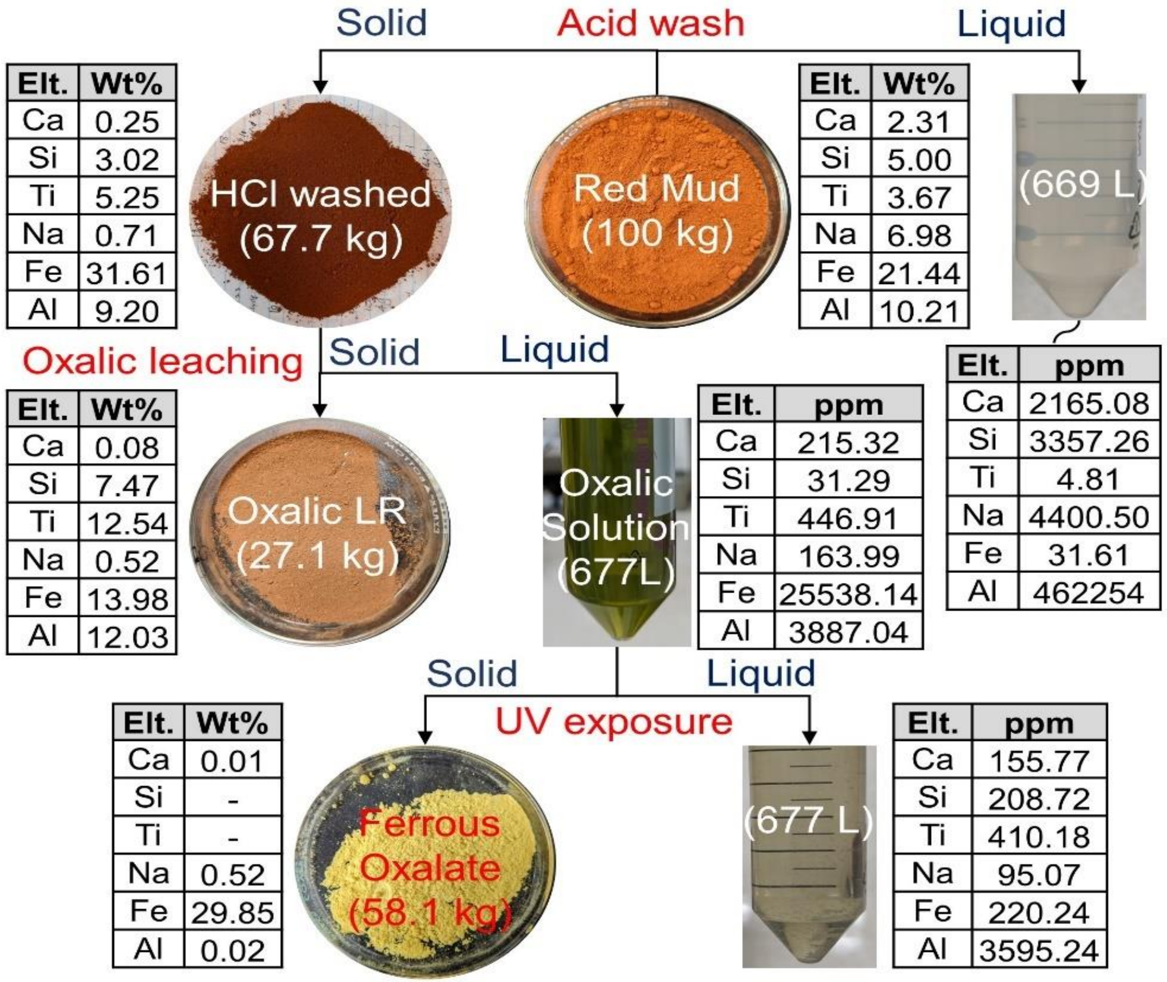
- From the iron and steel industry
  - Steel scrap (steelmaking only)
  - EAF dust (Zn & Fe) – Grensol
  - BF & BOS slag
  - Mill scale
- From other industries
  - Bauxite residue (40-60% hematite)
  - Titanomagnetite soil (73-85% magnetite)
  - Copper smelter dust (90-95% hematite)
  - Copper smelter slag (30-50% iron oxides)

Bauxite Residue: Hydrometallurgy

- A new iron source generating a new product
  - Large tonnage
  - Carbon-free
  - By-products
  - Hydrometallurgical

What are the potential routes to make it a viable technology?

- Investment in scale-up
- High risk – high gains technology
- Market development



HCl washed (67.7 kg):

Elt.	Wt%
Ca	0.25
Si	3.02
Ti	5.25
Na	0.71
Fe	31.61
Al	9.20

Red Mud (100 kg):

Elt.	Wt%
Ca	2.31
Si	5.00
Ti	3.67
Na	6.98
Fe	21.44
Al	10.21

(669 L):

Elt.	ppm
Ca	2165.08
Si	3357.26
Ti	4.81
Na	4400.50
Fe	31.61
Al	462254

Oxalic LR (27.1 kg):

Elt.	Wt%
Ca	0.08
Si	7.47
Ti	12.54
Na	0.52
Fe	13.98
Al	12.03

Oxalic Solution (677L):

Elt.	ppm
Ca	215.32
Si	31.29
Ti	446.91
Na	163.99
Fe	25538.14
Al	3887.04

Ferrous Oxalate (58.1 kg):

Elt.	Wt%
Ca	0.01
Si	-
Ti	-
Na	0.52
Fe	29.85
Al	0.02

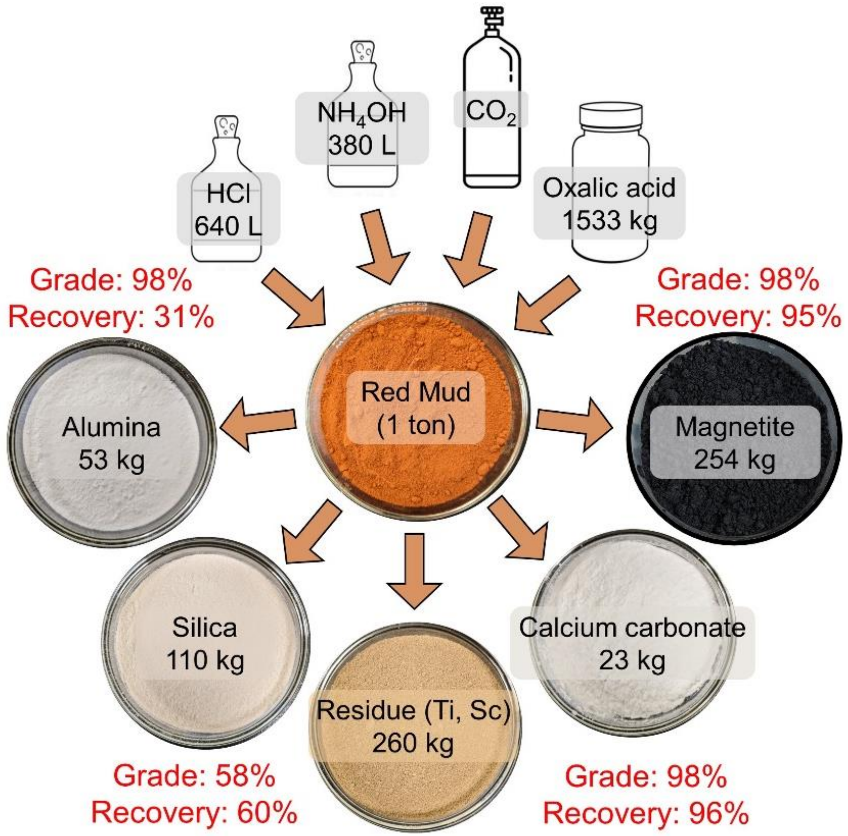
(677 L):

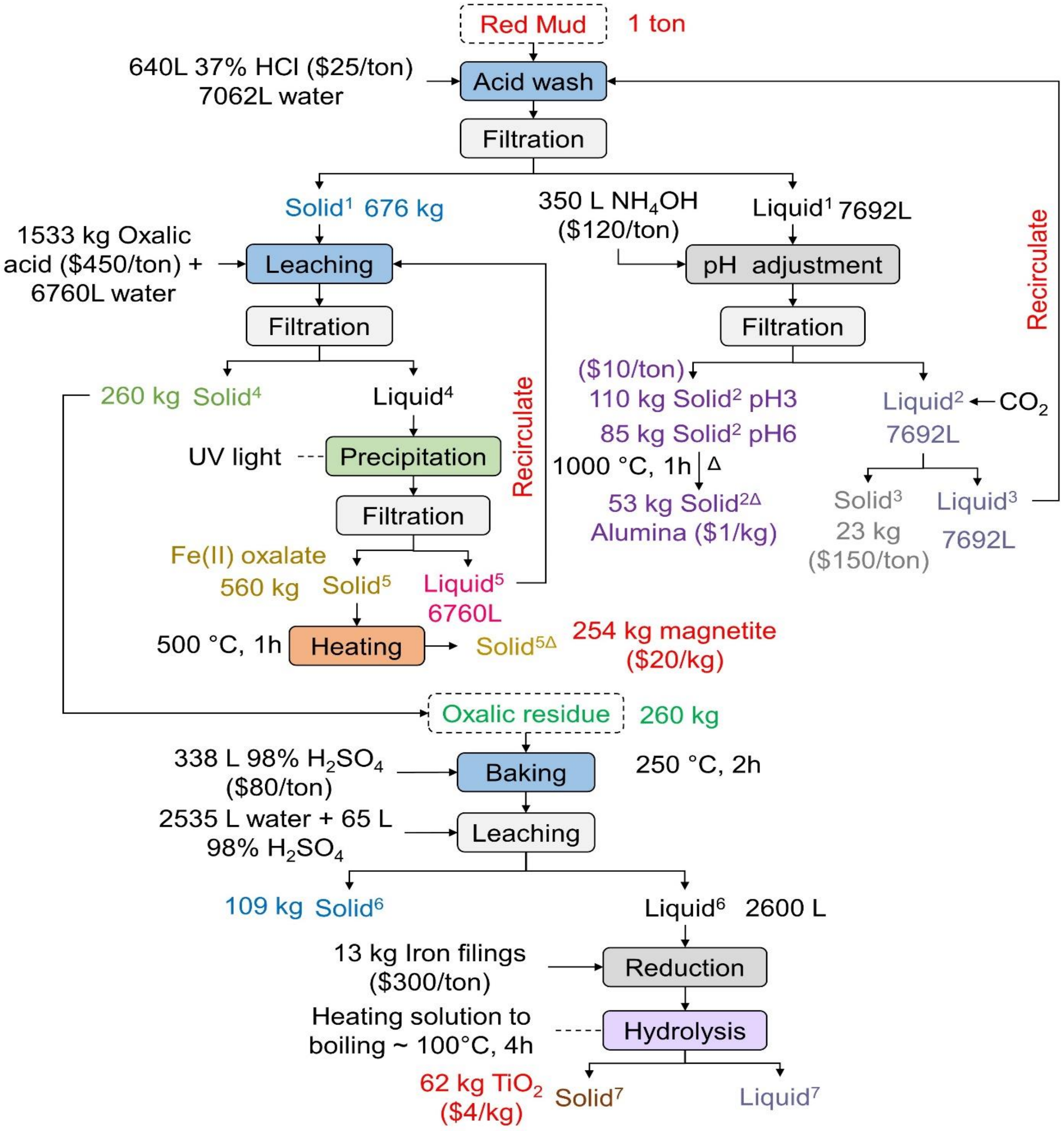
Elt.	ppm
Ca	155.77
Si	208.72
Ti	410.18
Na	95.07
Fe	220.24
Al	3595.24

Material	Market cost	Required / output	Cost
Input			
Red Mud	-	1 ton	-
HCl (37 %)	$25 / ton	640 L	$16.0
Oxalic acid (> 99%)	$450 / ton	1533 kg	$689.8
Output			
Ferrous oxalate (> 99%)	$10 / kg	581 kg	$5810.0
Net revenue (output – input) per ton of red mud treatment			+$5104.2

Bauxite Residue: Hydrometallurgy

- High purity products recovered
- Fully established at bench scale
- Materials balance required at scale-up
- Alternative source for iron-bearing product(s)





Applications of high-purity magnetite

- Magnetite is a common ore of iron used in steel production.

- It is attracted to magnets and can itself be magnetized.

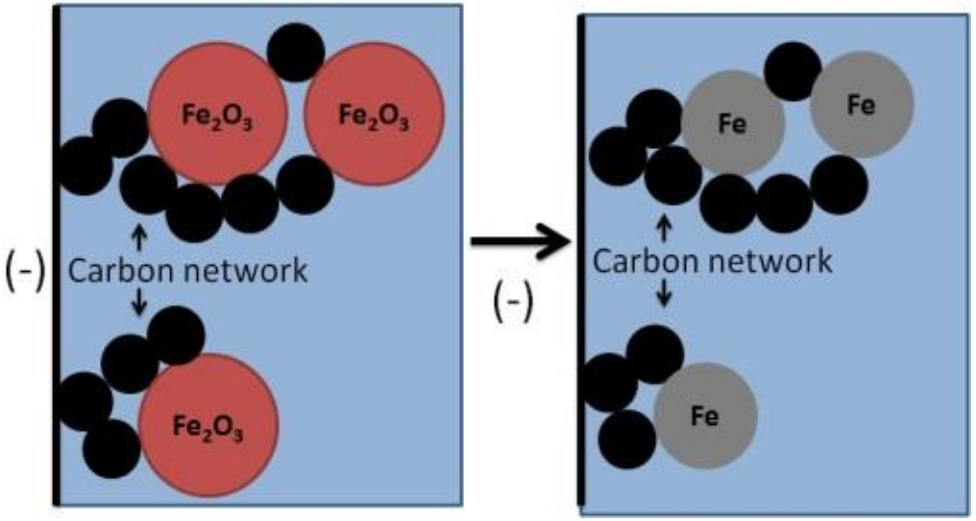
- It is used in the Haber-Bosch and Fischer-Tropsch processes as a catalyst, for the production of ammonia and hydrocarbons respectively; and as a tool in the degradation of contaminants from industrial processes.

- In medicine, ferrofluids of magnetite have been studied for the treatment of hypothermia. Other applications have been shown in hyperthermic therapies, in MRI contrast agents and in DNA extraction techniques.

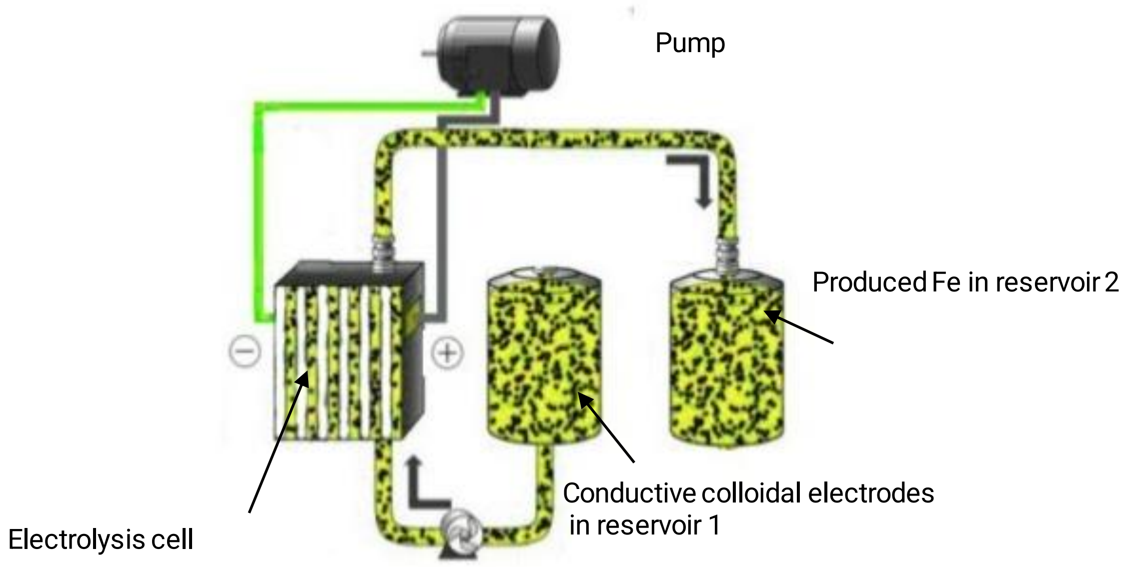
- Magnetite has been used in recording media, as a pigment material and for water purification.

Iron Production: Electrometallurgy

Iron Production via High Efficiency Flow Electrolysis



Electrolysis process with conductive colloidal electrodes



The design of flow electrolysis

Cathode: $Fe_2O_3\,(s) + 3H_2O + 6e^- \rightarrow 2Fe(s) + \; 6OH^-$

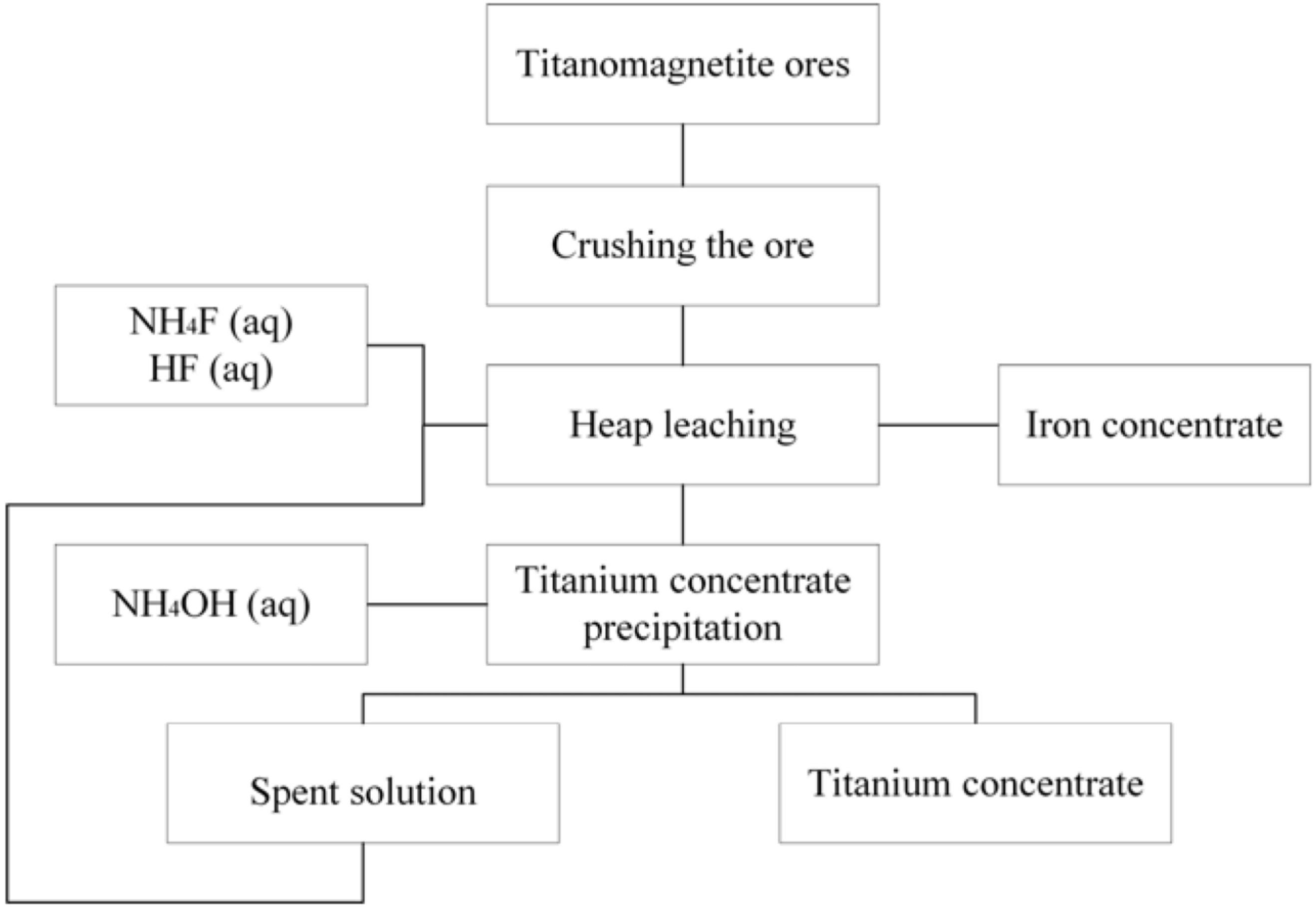
Anode: $6OH^- \rightarrow \frac{3}{2}O_2(g) + 3H_2O + 6e^-$

DOI: https://doi.org/10.1039/C4RA14576C

Titanomagnetite: Hydrometallurgy

- A source for iron and titanium concentrates

$FeTiO_3 \cdot Fe_3O_4 + 6NH_4F + 6HF + 0.25\ O_2 \rightarrow (NH_4)_3FeF_6 + (NH_4)_2TiF_6 + \mathbf{Fe_3O_4} + 3.5H_2O + NH_3$



https://doi.org/10.3390/min8010002

High-value and emerging important alloys

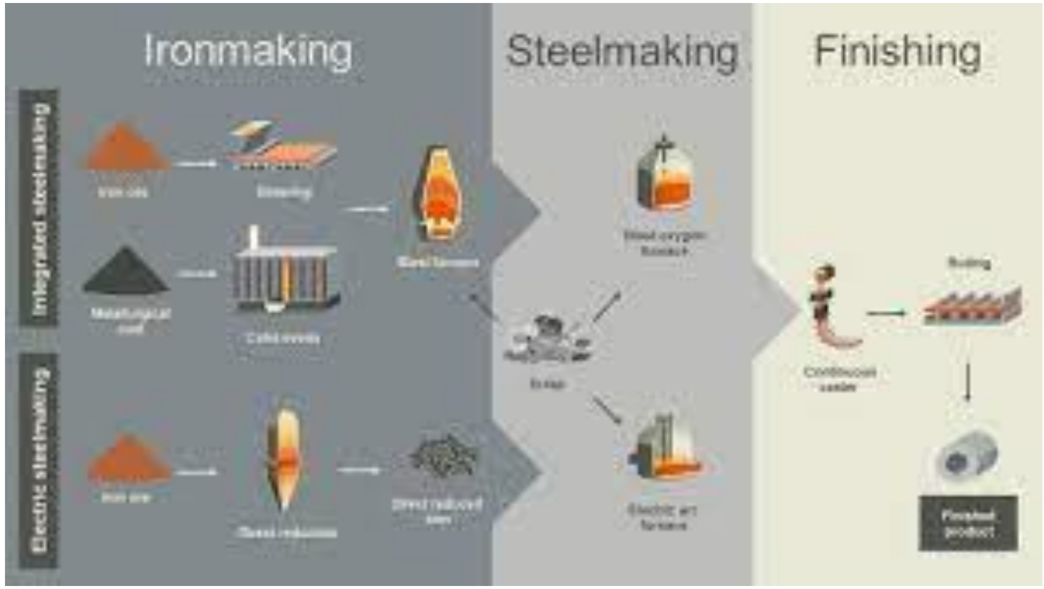
- Driven by high stiffness alloy demand
- Light-weight materials demand
- Demand for special steels –
  - ODS
  - High-silicon steels
  - Coated steels for corrosion and thermal protection
  - High entropy alloys
- Demand for advanced processes –
  - Near-net and net-shape manufacturing
  - Additive manufacturing
  - Subtractive manufacturing – *cast vs. wrought*
  - Efficient manufacturing supported by Machine Learning, Artificial Intelligence, Recovery & recycling, etc.
  - Use of non-fossil fuel processes

Future challenges:

- Installed capacity – 2 billion tons
- Cost of production by alternatives
- Environmental demand vs. fossil fuel
- Technical challenges – Electrometallurgy: inert anodes
  Metallothermic: thermodynamics & kinetics

We have to make bold advances!

Global Steel Production: Emissions



2 t CO_2/ t steel produced

Process Step	Direct CO_2 emission (tCO_2/t)
Coke plant	0.794
Sinter plant	0.200
Pellet plant	0.057
Blast furnace	1.219
BOS plant	0.181
Electric arc furnace	0.240
Bloom, slab and billet mill	0.088
Hot strip mill	0.082
Plate Mill	0.098
Section Mill	0.084
Pickling line	0.004
Cold mill	0.008
Annealing	0.049
Hot dip metal coating	0.059
Electrolytic metal coating	0.046
Organic coating	0.003

Source: BHP

Steel scrap: challenges

Copper and tin

Typical shredded scrap ~0.4wt% Cu

Primary and end-of-life steelmaking serve segregated markets, largely driven by the presence of copper.

Steel products: Maximum copper allowable (wt%)

Interstitial Free	Deep Drawing Quality	Drawing	Commercial	Structural	Fine Wire	Rebar
0.03	0.04	0.06	0.1	0.12	0.07	0.4

Courtesy: Katie Daehn, Cambridge University

Dilution

- ➢Used relatively pure iron to reduce the portion of tramp element amounts, the represented materials are direct reduction iron (DRI), hot briquetted iron (HBI), and pig iron.
- ➢The higher the impurities, the more relatively pure iron needed.

Pig Iron

DRI, Sponge Iron

HBI Iron